



Selection of CO₂ mitigation strategies for road transportation in the United States using a multi-criteria approach



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ABSTRACT

Carbon dioxide emissions from human activities are the primary cause of recent climate change. In the United States, the road transportation sector is one of the largest sources of these emissions. Any policies to reduce emissions must therefore include mitigation strategies for on-road transportation. The aim of this paper is to propose a multi-criteria method, Analytical Hierarchy Process, to rank various on-road emissions mitigation strategies including reduce, avoid, and replace strategies. The method's results are obtained based on a survey of transportation and climate science professionals. The Analytical Hierarchy Process was applied to two regional scenarios of a midsize-small city (Lubbock, Texas) and a metropolitan area (Dallas, Texas). To evaluate the effectiveness of these strategies, the Motor Vehicle Emissions Simulator model was run for Dallas. The aim of the model was to estimate the potential carbon dioxide mitigation for a given strategy allocation. Our survey identified no difference between the rankings of reduce, avoid, and replace strategies for our metropolitan and midsize-small city areas. *Reduce* strategies had the highest preference score of 40% followed by *avoid* strategies with 36% and *replace* strategies with 24%. An optimum mixed mitigation scenario would achieve reductions in carbon dioxide emissions of 17% by 2030 from 2010 levels. The contributions of this study are two-fold. First, we evaluate generic scenarios in detail and apply them to a real-world case study. Second, the approach is both simple and generalizable. Applications of this type of platform include ranking transportation strategies on mitigating carbon dioxide emissions, evaluating the strategies, prioritizing budgets, and developing assessments of mitigation potential.

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Contents

| | |
|---|-----|
| 1. Introduction | 961 |
| 2. Climate change, CO ₂ emissions, and the transportation sector | 961 |
| 3. Sustainable road transportation | 962 |
| 4. AHP multi-criteria approach | 962 |
| 4.1. About the AHP | 963 |
| 4.2. Data collection | 963 |
| 4.3. AHP results | 964 |
| 5. MOVES emission inventory model | 964 |
| 5.1. MOVES model description and parameters | 965 |

Abbreviations: AHP, Analytical Hierarchy Process; BAU, Business As Usual; CLEAN-TEA, Clean, Low-Emission, Affordable New Transportation Efficiency Act; COPERT, Computer Program to estimate Emissions from Road Traffic; EPA, Environmental Protection Agency's; HOV, High Occupancy Vehicle; HI, Highest Implementation; I/M, Inspection and Maintenance; LI, Lowest Implementation; MOVES, Motor Vehicle Emissions Simulator; MCDM, Multi-Criteria Decision Making; MVEI, Motor Vehicle Emission Inventory; PROMETHEE, Preference Ranking Organization Method for Enrichment Evaluations; SUTP, Sustainable Urban Transport Project; VMT, Vehicle Miles Traveled; WWF, World Wildlife Fund

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| | |
|---|-----|
| 5.2. MOVES model simulation scenarios | 965 |
| 5.3. MOVES model simulation results | 966 |
| 6. Conclusion and recommendations | 966 |
| Appendix A. Survey | 967 |
| Overview | 967 |
| Criteria | 967 |
| Reduce air pollution | 967 |
| Reduce traffic congestion | 967 |
| Reduce investment cost | 967 |
| Save more natural environment | 967 |
| Strategies (alternatives) | 967 |
| Comparison scale | 968 |
| Definitions | 968 |
| Metropolitan area | 968 |
| Small city | 968 |
| Criteria comparison | 969 |
| Strategy comparison | 970 |
| References | 970 |

1. Introduction

Climate is changing as a result of human activities, primarily due to emissions of carbon dioxide (CO₂) and other greenhouse gases (GHGs) from fossil fuel consumption [1]. CO₂, methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF₆) have been identified as the primary GHGs responsible for human-induced climate change [2–4]. Of these GHGs produced by human activities, CO₂ has the greatest impact due to the sheer volume of its emissions from fossil fuel combustion in several sectors including electricity generation, transportation, agriculture, commercial, and residential activity [2,4–6].

In the United States, GHG emission levels from the transportation sector have risen more than any other sector over the last two decades [7]. The transportation sector is the second largest source of GHG emissions, with CO₂ making up 95% of those emissions [5,8]. The majority of greenhouse gas emissions are from passenger cars and light and heavy trucks [7,9–11]. U.S. light-duty vehicles' CO₂ emissions alone are comparable to the total CO₂ emissions of other industrialized countries such as Germany and Japan [5]. The impact of this sector on U.S. emissions, together with its vital role in daily life, make the U.S. road transportation and its planning the key to achieving long-term CO₂ mitigation.

One of the main steps in transportation planning and policy-making is budget prioritizing. This process often includes ranking available mitigation strategies [12], which in turn requires objectives and criteria to be set. In the case of major planning, there are usually multiple objectives, which require multi-criteria selection between a series of possible scenarios. Single criteria approaches primarily aim to maximize benefits while minimizing costs. In contrast, Multi-Criteria Decision Making (MCDM) techniques reflect essential characteristics of the decision process. Analytical Hierarchy Process (AHP) is the most popular multi-criteria method [13]; it provides decision makers with realistic strategy ranking. Once the strategies are scored based on the AHP, emission inventory models can be used to estimate the goals achieved by a given action.

Emission inventory models such as MOVES [14], COPERT [15], MOBILE [16], and MVEI [17] can be used to estimate road transportation emissions. These models provide an effective scenario implementation perspective on transportation pollutants [18]. The U.S. Environmental Protection Agency's (EPA) MOVES (Motor Vehicle Emissions Simulator) is the most advanced emission estimator [19]. This model approximates pollutants and

greenhouse gas emissions such as HC, CO, CO₂, NO_x, CH₄, N₂O, PM₁₀, and PM_{2.5} from motor vehicles, according to different conditions and parameters such as vehicle-class population, vehicle mileage traveled, fuel type, speed distribution, road type, and meteorological data. The model is comprehensive and applicable for big cities and large network sizes with high degree of uncertainty and complexity [14].

The objective of this study is to use AHP to prioritize on-road CO₂ mitigation strategies for policy-level transportation funding allocation. AHP priorities were obtained based on an online survey completed by mainly transportation and climate science professionals, the output of which was then used as input to the MOVES model to assess the potential of the CO₂ mitigation scenarios.

We first review on the sources of CO₂ emissions in the United States, and the overall relevance of the transportation sector to human-induced global warming in Section 2. We then review aspects of sustainable road transportation in Section 3. The AHP analysis and MOVES model are discussed in Sections 4 and 5, followed by our conclusions and recommendations in Section 6.

2. Climate change, CO₂ emissions, and the transportation sector

Earth's surface temperature has increased by 0.8 °C over the 20th century and is expected to continue to increase by 1.4–5.8 °C during the 21st century, depending on the magnitude of human emissions of CO₂ and other GHGs [20,21]. The impacts of a warming planet include increases in temperature, shifts in precipitation patterns, rising sea level, reductions in ice and snow cover, and an increase in the frequency and/or severity of extreme weather events including heat waves, droughts, floods [22], and hurricanes [23]. In many parts of the world, these changes are already affecting agriculture [24], ecosystems, energy, human health [25], infrastructure, water resources, and the economy [26–28].

Due to the magnitude of its emissions, CO₂ is the primary driver of human-induced climate change [29–31]. CO₂ is produced primarily from the burning of fossil fuels associated with transportation, electricity generation, and heating and cooling in buildings. Additional emissions come from deforestation, land use changes, and cement manufacture [20,32–34]. While China recently overtook the U.S. in terms of its total annual emissions, the U.S. is responsible for approximately one third of all carbon emissions since the Industrial Revolution and still maintains the

highest per capita rate of CO₂ emissions of any large nation in the world [35].

In the U.S., transportation is responsible for nearly one-third of total emissions (Fig. 1(a)). Of those emissions, over one-third can be attributed to passenger cars and another one-third to light and heavy trucks (Fig. 1(b)). This highlights the significant impact of on-road transportation policies in reducing CO₂ emissions. CO₂ emission mitigation not only reduces the influence of humans on climate, but it can also potentially reduce air pollution, which in turn benefits human health and natural ecosystems as well as conserving finite resources of oil and other fossil fuels.

In any state, transportation emissions are an important source of CO₂ [36]. For the purpose of this study, however, we needed to identify a possible case study area. Annual CO₂ emissions in Texas are substantially higher than any other state in the U.S.; within the state of Texas, both large urban areas such as Dallas and smaller cities such as Lubbock have relatively high per capita emissions, with large contributions from transportation [37,38]. For this reason, we selected these two locations as case studies to assess the potential for CO₂ mitigation from the transportation sector.

3. Sustainable road transportation

Literature contributes to sustainable road transportation field in two levels. Firstly, transportation sector emission is estimated in various ways. Secondly, different policies to reduce the emission are investigated. Researches in the first group are addressed by several studies in the U.S. [19,39,40], Europe [41–43], Asia [44], and Australia [45]. Emission mitigation policies include quite a lot of scenarios, which are used in European countries [46–49], Asia [9,50,51], Africa [52], Australia [53], and the U.S. [54–56].

Policies to reduce CO₂ emissions from road transportation encompass a wide range of strategies. Common examples include high efficiency vehicles [54], travel demand management (flexible hours, teleworking) [55], shifting from personal car to public transport [53,55], alternative fuels (hydrogen, electricity, biofuel) [54,56], various types of taxation (road toll, parking charges) [10], reducing engine weight [57], zero-carbon alternatives (cycling and walking) [10,53], increasing road capacity [10,50], Soft policies High Occupancy Vehicle (HOV) lanes [10,53]. Each of these strategies targets a specific source of emissions that should be clearly identified and investigated. All of the strategies for reducing emissions can be classified in different ways. Table 1 provides

a list of CO₂ mitigation strategies derived based on previous research studies.

In the U.S., under the Clean, Low-Emission, Affordable New Transportation Efficiency Act (CLEAN-TEA) introduced in March 2009, local governments with a population of over 200,000 are required to determine a plan to mitigate GHGs from the transportation sector [62]. Transport-related climate action plans in different cities are listed in the Sustainable Urban Transport Project (SUTP). An example of these cities is the city of Houston, TX, which published an Emission Reduction Plan in mid-2008. Its goals consisted of (1) replacing traffic lights with LED technology, (2) replacing older vehicles with modern, more fuel efficient cars and trucks, and (3) introducing hybrid vehicles and other new technology [63].

Transportation systems are usually complex and correlate with contextual socio-economic and environmental factors. Setting targets and incorporating strategies for sustainable transportation need to integrate both direct and indirect impacts of transportation. Section 4 of this research attempts to assess the different transport-related strategies that seem to be instrumental for reducing CO₂ emissions in cities with different regional characteristics and ranks the strategies using a multi-criteria analysis. Ranking these strategies is crucial due to budget and time constraints.

4. AHP multi-criteria approach

Multi-criteria analysis can be used to solve problems with multiple objectives by assessing multiple solutions, yielding results that are more effective, clear, and logical than the corresponding single-criteria approaches [13,64]. In most transportation planning situations, multiple beneficiaries are involved and each brings along a different criterion. The need to incorporate economic, environmental, social, and health considerations into transportation planning, means that decision-making in this sector is ideally suited to the application of multi-criteria approaches.

MCDM methodology is implemented by various techniques such as WSM, WPM, AHP, PROMETHEE, ELECTRE, TOPSIS, CP, and MAUT [13,65–67]. Each of the methods has particular advantages and disadvantages. AHP is the most popular method [13] and the most widely-used multi-criteria tool in transportation planning [68] including selecting alternative options in multiobjective planning [51] and screening transport projects [52]. It has also been applied in several studies integrated with other methods

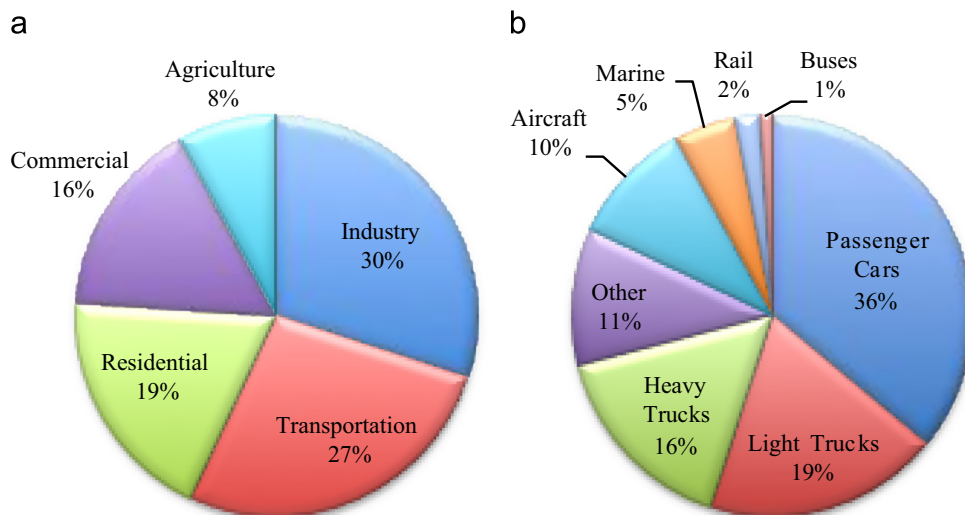


Fig. 1. (a) Transportation share of U.S. emissions and (b) transportation emission by mode (2002) [5].

Table 1
Different classification of CO₂ mitigation strategies.

| Distinction | Scenario name | Scenario description | Scenario examples |
|--|--------------------|--|---|
| Integration into different types of transportation policies and planning [58] | Physical policies | Affecting element of physical infrastructure | Public transportation, land use, walking and cycling, road construction, and freight transportation |
| | Soft policies | Non-tangible policies aiming to bring about behavioral changes to people | Car sharing and car-pooling, teleworking and teleshopping, eco-driving, public outreach and raise awareness through advertising campaigns |
| Level of technical contribution to Environmental Sustainable Transportation (EST) [59] | Knowledge policies | Emphasizing on the role of investment in research and development to find a sustainable model of mobility for the future | External knowledge to produce new product, incentives for R&D |
| | EST1 | Looking for only technical solutions | Hybrid and electric cars based on renewable energy |
| | EST2 | Managing mobility and ignoring technological development | Restricting and shifting vehicles volume, speed limit in urban areas, prohibition of night-time road freight traffic |
| Tackling road transportation GHG emissions [60] | EST3 | Combining the mechanisms of the EST1 and EST2 | A combination of the other two categories |
| | Avoid | Avoiding unnecessary energy consumption and promote other modes of transportation | Road taxes and parking prices, public transport, HOV lanes and carpooling, teleworking, cycling and walking |
| | Reduce | Reducing GHG emissions per passenger kilometer traveled | More fuel-efficient vehicles, improve fuel-efficiency standards |
| Ease congestion and emission mitigation [61] | Replace | Replacing fossil fuels with low-carbon fuels | Clean-fuel vehicles such as electricity and biofuel powered vehicles |
| | Capacity-based | Increasing roadway's vehicle throughput capacity | Expanding infrastructure, increasing existing roadway utilization |
| | Demand-based | Reducing vehicle travel volume | Road pricing, fuel pricing |
| | Vehicle-based | Reducing emissions through cleaner vehicles and fuels | Improve vehicle-efficiency and fuel-efficiency standards |

Table 2
Saaty's scale for AHP pairwise comparisons [65].

| Weight | Description |
|--------------------|------------------------------|
| 1 | Equal importance |
| 3 | Moderately more important |
| 5 | Strongly more important |
| 7 | Very strongly more important |
| 9 | Dominant importance |
| 1/3, 1/5, 1/7, 1/9 | Reciprocals |

such as Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) [68] and Visekriterijumsko KOMpromisno Rangiranje or VIKOR [69] techniques for decision making and planning processes.

This study employs a survey to perform the AHP method. The objective of the study is to evaluate and prioritize the strategies that can reduce CO₂ emissions from road transportation. The outcome of this prioritization would be crucial for policyholders as it can be used to optimize their investment strategies. The proposed framework is described in detail next.

4.1. About the AHP

AHP is one of the best-known and most widely used multi-criteria analysis approaches [70]. Lacking quantitative ratings, AHP can help policymakers evaluate the importance of strategies for a specific issue. The basic procedure to carry out the AHP consists of the following steps:

- Establish a hierarchy for the problem including goals, alternatives to reach to those goals and criteria for evaluating the alternatives.
- Set criteria priorities by pairwise comparison (weighing).
- Conduct a pair wise comparison of alternatives on each criterion (scoring).
- Obtain an overall relative score for each alternative [70].

Pair-wise comparison is performed using a matrix, made up of Saaty's fundamental scale of 1–9. This scale is used in matrices to find relative criteria's weights and to compare the alternatives associated with each criterion. Table 2 summarizes the fundamental ratio scale. All final weighted coefficients are shown in matrices. Alternatives and criteria can be ranked based on the overall aggregated weights in matrices. The alternative with the highest overall weight would be the most preferable.

To apply the AHP method in this study, alternatives and criteria related to the objective needs to be defined. As described in Table 1, Canada's World Wildlife Fund (WWF) [60] exercised three main strategies to tackle road transportation GHG emissions: avoid, reduce, and replace. This classification is comprehensive and well defined. These three strategies were selected as the alternatives for this study's AHP process. Corresponding criteria were defined to incorporate economic, environmental, social, and health concerns into the process and include: reduce transportation investment cost, save more natural environment, reduce traffic congestion, and reduce air pollution. Finally, the goal was set to reduce CO₂ emissions. The basic outline of the AHP method in this study is illustrated in Fig. 2.

4.2. Data collection

For the purpose of data collection, a survey was developed to collect information on pairwise comparison of the predefined CO₂ emissions reduction criteria and alternatives (see Appendix A). The survey participants were mainly transportation and climate science professionals. The survey was approved by Texas Tech University Institutional Review Board and was carried out through Survey Monkey website. The structure of the survey consisted of three sections: (1) demographics, (2) criteria comparison, and (3) strategy comparison. The first set of questions intended to capture the demographic information of the survey participants and included their states, city, professional background, and job affiliation. Fig. 3 summarizes the background and job affiliation data of 71 experts who completed the survey.

The majority of the responses came from Texas 27%, Michigan 13%, and Georgia 10%. Other states including Alaska, California, Connecticut, DC, Illinois, Indiana, Minnesota, New York, Oregon, Pennsylvania, Virginia, Washington, and Wisconsin had lower rate of participation (less than 10% each) compared to the former three. Finally, 32% of the participants worked in metropolitan areas with population of more than half a million.

The next set of questions focused on pair wise comparison of the previously defined criteria given two regional scenarios of a midsize-small city (Lubbock, TX) and metropolitan area (Dallas, TX). The incorporation of two regional scenarios was due to the fact that different regional characteristics (metropolitan or midsize-small city) have different transportation patterns, policies, and also different ecological locations. For this reason, ranking of the alternatives might be different. To investigate this fact, participants answered the second and third sets of questions for the two regions, midsize-small city (Lubbock, TX) and metropolitan area (Dallas, TX), individually. The last section centered on the pair wise comparison of the mitigation alternatives, given a certain predefined criteria discussed in Section 4.3.

4.3. AHP results

Based on the AHP results shown in Table 3 below, our survey identified no difference between the rankings of reduce, avoid, and replace strategies for our metropolitan and midsize-small city areas. Rather, the results indicated the importance of cost and feasibility associated with the predefined strategies in selection of the survey participants. In other words, the reducing strategy was shown to be more favorable as it is generally cheaper and more feasible in comparison to replacing strategies. This result may be of interest to policyholders, to prioritize their planning efforts regarding CO₂ emission strategies and invest accordingly. In Section 5, we use the MOVES model to estimate the potential effect of each scenario on overall CO₂ mitigation. The AHP is also used to evaluate the final CO₂ mitigation strategy proposed based on the combined percentages of each strategy.

5. MOVES emission inventory model

The goal of this section is to approximate the amount of CO₂ emissions generated under different mitigation scenarios. Emission inventory models used to estimate the amount of pollutants from motor vehicles include COPERT (Computer Program to estimate Emissions from Road Traffic), which is the most frequently used model in European countries such as Spain [71], Denmark [43], and Sweden [72] and is also one of the choices for road network emission modeling in Australia [45] and Asia [18]. However, both COPERT III and 4 have been determined to under-estimate emissions [43,45]. The MVEI (Motor Vehicle Emission Inventory) model was developed by California Air Resources Board and used to evaluate pollutants released by the road transportation network at several regional levels. While other GHGs (CH₄, N₂O) are still

Table 3
Overall score for each option for metropolitan area and midsize-small city.

| Regional scale | Reduce strategies | Avoid strategies | Replace strategies |
|--------------------|-------------------|------------------|--------------------|
| Metropolitan area | 0.40 | 0.36 | 0.24 |
| Midsize-small city | 0.40 | 0.36 | 0.24 |

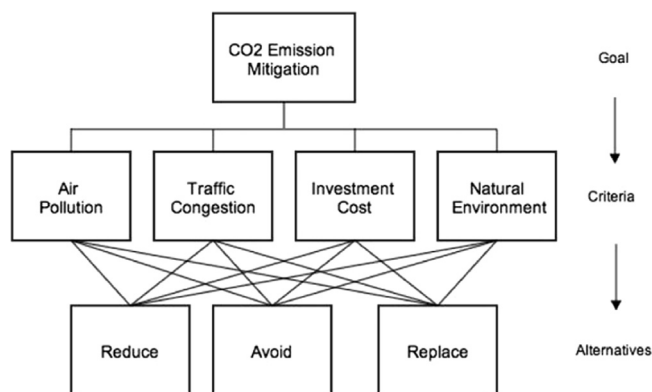


Fig. 2. Structure of AHP method for this study.

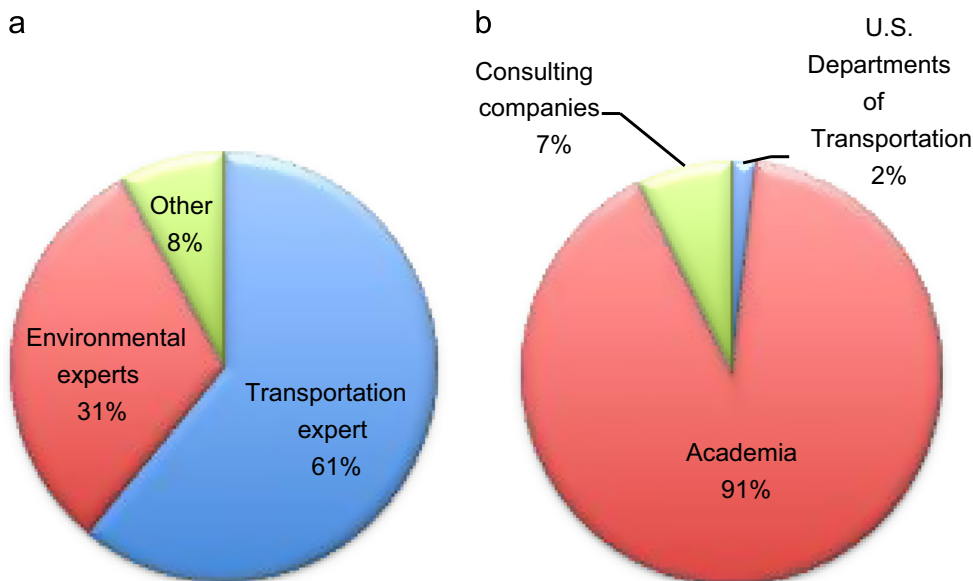


Fig. 3. Data description (a) experts' background and (b) experts' job affiliation.

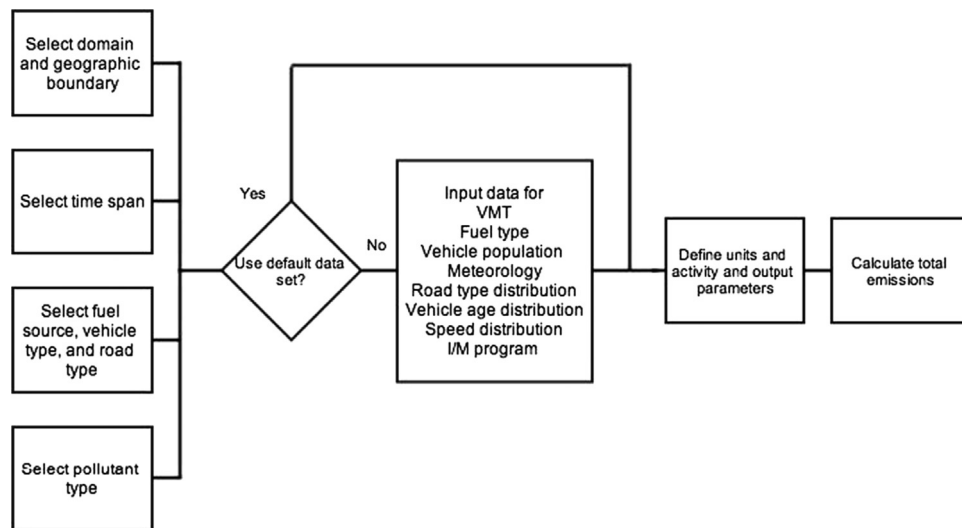


Fig. 4. MOVES model structure.

Table 4
Scenario's description and type.

| Scenario | Implementation | Description |
|----------------------------------|---|--|
| Base year 2010 | Current conditions | Study the baseline condition in calendar year 2010 |
| BAU projection for the year 2030 | Growth in fleet size is 1.5% per year [76] Growth in activity (VMT) is 50% by 2030 compared to 2010 [77] | Project the CO ₂ emissions in 2030 if no mitigations are adopted. This scenario is a benchmark to assess the other scenarios. |
| Reduce scenario-LI | Average fleet age reduced by 5 years from BAU | Due to support vehicle retirement program. Assess the minimum possible reduction from this application. |
| Reduce scenario-HI | Average fleet age reduced by 10 years from BAU | Due to support vehicle retirement program. Assess the maximum possible reduction from this application. |
| Avoid scenario- LI | Current percentage of work at home is 2.6% in Dallas. Growth in this proportion 10% per year [78] Reduction in annual VMT per telecommuter is 5120 miles from BAU [79] | Facilitating tele-conferencing and working from home. Assess the minimum possible reduction from this application. |
| Avoid scenario-HI | Current percentage of work at home is 2.6% in Dallas. Growth in this proportion 10% per year [78] Reduction in annual VMT per telecommuter is 7856 miles from BAU [79] | Facilitating tele-conferencing and working from home. Assess the maximum possible reduction from this application. |
| Replace scenario-LI | 25% of cars are replaced by PHEVs by 2030 from BAU [80] | Supporting zero-tailpipe emissions engines powered by renewable energy. Assess the minimum possible reduction from this application. |
| Replace scenario-HI | 50% of cars are replaced by PHEVs by 2030 from BAU [81] | Supporting zero-tailpipe emissions engines powered by renewable energy. Assess the maximum possible reduction from this application. |

needed to be included in this model, MVEI is a practical model for evaluating different scenarios and performing sensitivity analysis [44]. Finally, the U.S. EPA has developed MOVES2010 (MOTOR Vehicle Emissions Simulator) to replace EPA's previous emission model, MOBILE6. MOBILE6 did not consider the effect of speed on emissions [62]. In contrast, MOVES is capable of estimating different types of emissions from on-road mobile sources under both default and customized databases. Here, we use MOVES to evaluate the effectiveness of the CO₂ mitigation scenarios derived from the AHP method described above. Advantages resulting from using the MOVES model include defining time spans, geographical boundaries, on-road vehicle types, road types, and a wide range of pollutants. A detailed description of the MOVES model structure and modeling scenarios as applied to Dallas road networks are presented in Sections 5.1–5.3. Due to lack of detailed data for smaller cities, the model could not be applied to Lubbock.

5.1. MOVES model description and parameters

MOVES2010 is capable of using U.S. default databases and importing custom data-sets that include data such as vehicle year,

vehicle type, meteorology-related data, vehicle miles traveled (VMT), average speed distributions, road type distributions, ramp fractions, fuel formulation and supply, and Inspection and Maintenance (I/M) program parameters. Fig. 4 shows the structure of MOVES2010 model and the procedure in more detail.

The MOVES model can be utilized for performing sensitivity analyses, evaluating scenarios, and performing time series analysis the outcome of which can be used in other models [73]. Several states have used the MOVES models as a part of their transportation planning such as Washington [74], New York [19], Nevada [73] and more specifically Texas [39,40]. This study customizes the MOVES model for Dallas, Texas in order to estimate and analyze the CO₂ emissions associated with the AHP-proposed mitigation scenarios.

5.2. MOVES model simulation scenarios

Due to the large number of input parameters in MOVES model [75], we consider only two variations for each scenario. These variations are based on the level of implementation of each scenario and, as such, are categorized as the lowest and the

highest implementation (LI and HI). The scenarios were developed based on the following assumptions: (1) a target year of 2030, (2) a base year of 2010, and (3) a Business As Usual (BAU) projection. A description of each scenario and its category are summarized in Table 4.

5.3. MOVES model simulation results

Simulation results were assessed in terms of total mass (Kg) of CO₂ emissions including those generated by both distance traveled and car ignition. Both rural and urban roadways were considered as different inputs for road types and both passenger cars and trucks were included. To achieve more precise results, input data for Dallas County is used instead of default national data set. Table 5 summarizes estimated CO₂ reduction rates in terms of percentages as well as the total quantities of CO₂ for the base and BAU scenarios.

Following the BAU projection, simulation results showed an annual growth in transportation-related CO₂ emissions of 0.73%, only slightly higher than the nation-wide value of 0.7% [82]. This indicates that Dallas's CO₂ emissions annual growth based on BAU projections is not significantly different from the national CO₂ emissions annual growth.

Simulation results showed that based on the highest level of implementation *avoid* scenario had the highest impact on CO₂ mitigation, followed by *reduce* and *replace* scenarios. *Avoid* scenario also had the highest change in mitigation percentages, by shifting from the lowest to the highest implementation. *Reduce* scenario has the maximum impact based on the lowest level of CO₂ mitigation scenario implementation.

To achieve optimum mitigation results, the outcomes from pre-defined AHP process were used to develop a mixed scenario including all the pre-defined scenarios. Based on the AHP results the distribution of preferences among scenarios was 40%, 36%, and 24% of implementation for *reduce*, *avoid*, and *replace* scenarios, respectively. These percentages were applied to the highest implementation for each scenario to from the optimal mitigation strategy. Table 6 shows the description and the result of implementing the mixed scenario. According to this mixed scenario the total amount of CO₂ mitigation that resulted was 17.2%, similar to the results from the high implementation of the *avoid* scenario.

6. Conclusion and recommendations

Transportation is a significant source of carbon emissions. Reducing those emissions is the key to long-term CO₂ mitigation in order to stabilize the impact of human activities on climate. The

Table 5
Total CO₂ emissions and CO₂ mitigation compared to BAU for each scenario.

| Base | BAU | Reduce scenario | | Avoid scenario | | Replace scenario | |
|--------------------------------------|--------------------------------------|-----------------|--------|----------------|--------|------------------|--------|
| CO ₂ (10 ⁹ Kg) | CO ₂ (10 ⁹ Kg) | LI (%) | HI (%) | LI (%) | HI (%) | LI (%) | HI (%) |
| 4.12 ^a | 4.77 ^a | 9.33 | 12.23 | 7.17 | 17.65 | 3.35 | 6.71 |

^a Numbers are rounded.

Table 6
Mixed scenario based on AHP results.

| Mix scenario | Description | Total CO ₂ reduction compared to BAU |
|---------------------------------------|---|---|
| Implementation by 2030 related to BAU | Average fleet age reduced by 4 years Reduction in annual VMT per telecommuter is 2828 miles 12% of cars are replaced by PHEVs | 17.2% |

objective of this paper was to investigate and evaluate transportation strategies on mitigating CO₂ emissions in a representative large and a midsize-small city in the United States.

In the U.S., the transportation sector is one of the primary and fastest growing sectors of human activities that release CO₂ by burning fossil fuels. Among different modes of transportation, passenger cars and trucks are most responsible for increasing emissions; hence, they were selected as the focus of this research.

To find the most effective strategies for reducing CO₂ emissions from transportation, we considered multiple criteria and alternatives. The alternatives were prioritized based on transportation and climate science professionals' opinions through AHP multi-criteria method. To explore the independency of this prioritization on city characteristics, AHP was applied to the cities of Dallas and Lubbock in Texas, each having a high proportional share of CO₂ emissions attributable to transportation [37,38] and each having a distinct character with one being a metropolitan and the other a midsize-small city.

The results of the AHP method indicated that *reduce* strategies had the highest preference score of 40%, followed by *avoid* strategies with 36% and *replace* strategies with 24%. Applying the MOVES model to the base scenario in the year 2010 and the Business As Usual (BAU) scenario projection for the year 2030, for each scenario based on two levels of implementation (the highest and the lowest), showed that based on the highest level of implementation *avoid* scenario have the highest impact on CO₂ mitigation, followed by *reduce* and *replace* scenarios. The *avoid* scenario also had the highest change in mitigation percentages, by shifting from the lowest to the highest implementation. The *reduce* scenario had the maximum impact, based on the lowest level of CO₂ mitigation scenario implementation.

To achieve optimum mitigation results, the outcomes from pre-defined AHP process were used to develop a mixed scenario including all the pre-defined scenarios. A total CO₂ reduction of 17.2% resulted from applying this mixed scenario, similar to the results from the high implementation of *avoid* scenario. The results of this research are not quite comparable to the other studies due to its unique mixed scenario structure. The outcomes of the scenarios as well as the AHP ranking are related to regional factors and level of implementation and cannot be matched. However assuming similar scenario descriptions, the result in [46] showed that *reduce* scenario is the scenario with the lowest energy demand and the highest impact on CO₂ mitigation, followed by *avoid* and *replace* scenario. This result is aligned with the result achieved in this study by the lowest level of implementation.

This paper explores a framework to evaluate strategies to mitigate CO₂ emissions and prioritize them based on a city's attributes and characteristics. The outcome of this research highlighted the efficacy of different CO₂ mitigation strategies under different urban settings. This is instrumental to policymakers in fine-tuning their planning and policies to better meet their budget and time constraints. Future research is needed to integrate other GHGs and their contribution to both climate change and air pollution, as well as to explore multiple scenarios and integrate an appropriate cost analysis for evaluation of each strategy and their feasibility.

Appendix A. Survey

Human activities are altering the atmospheric CO₂ level. This extra CO₂ is leading to “global warming”. Reducing CO₂ emissions not only reduces global warming, but also is beneficial in many other ways. The proposed survey intends to evaluate CO₂ emission reduction strategies based on an iterative pair-wise comparison process called Analytic Hierarchy Process (AHP) and identify the one which is perceived to be the most effective. Enclosed is a short survey asking questions that many help us to understand this issue. No information will be gathered that could personally identify you. Thank you for your time and consideration in helping us answer these questions. This research has been approved by the Texas Tech University Institutional Review Boards.

Demographic Information:

In what U.S state are you currently employed?

What is the type of your employment?

University ☐ DOT (Department of Transportation) ☐ Consulting-Transportation ☐
Consulting-Climate Science ☐ Others please explain -----

What is the field of your expertise?

Transportation ☐ Environmental and climate science ☐ others please explain: -----

Overview

In this survey, several CO₂ emission strategies are evaluated through pairwise comparison and based on multiple criteria. These criteria and strategies together with a comparison scale are elaborated below:

Criteria

In this research, four main criteria are being considered for pairwise evaluation of CO₂ emission strategies:

Reduce air pollution

Air pollution includes substances in the air such as fine particles, and noxious gases that are believed to be harmful to human health. Relatively, reducing air pollution means to perform actions that can reduce air pollution and prevent or reduce harmful effects on human health.

Reduce traffic congestion

Congestion often means stopped or stop-and-go traffic. Reduce traffic congestion refers to less vehicles on roadways so drivers can save time due to shorter travel times.

Reduce investment cost

Investment in transportation infrastructures means expanding and adding roads or public transportation facilities. If transportation needs can be addressed through methods other than construction, the funds intended to be spent on expanding transportation infrastructure can be spent on other critical public projects.

Save more natural environment

Natural resources are all the things on Earth that support life. Such as plants, animals, and water are natural resources. Public sector projects and in particular, transportation developments have the potential to impact on natural habitats, affecting wildlife and plant species. Saving more natural environment, provide opportunities to protect sensitive sites and minimize damage to ecology (especially agriculture lands, wild life, and woodlands).

Strategies (alternatives)

All potential solutions to CO₂ emission reduction are categorized under the following strategies: avoid using personal car, reduce CO₂ emissions per kilometer, and replace fossil fuel. Following table shows different examples based on these three strategies in the transportation industry.

| Strategy | Policy | Implementation |
|--|-------------------------|---|
| Reduce CO ₂ emissions per kilometer | Transportation planning | Use GPS to send real-time traffic data and informing shortest path Light synchronizing |

| | | |
|--------------------------|---|--|
| Avoid using personal car | Effective vehicle | Improve fuel-efficiency standards Improve vehicle-efficiency standards |
| | Demand management | Increase road taxes and parking prices Increase fuel taxes Reduce trip need by facilitating work at home and online shopping |
| | Public transport | Increasing the capacity and quality of public transport Emphasis on metro and light rail Increasing trip size |
| | Car sharing | Facilitating modal shift between public transit Supporting vanpooling and carpooling Private car sharing |
| Replace fossil fuel | Environmentally friendly transportation | Encourage people to choose biking or walking Creating specific roads and path |
| | Alternative fuels | Develop clean-fuel vehicles, (electricity, biofuel powered vehicles) Equipped public busses and taxis with clean fuels |

Comparison scale

| | |
|---|----------------------------|
| 1 | Strongly disagree |
| 2 | Disagree |
| 3 | Neither agree nor disagree |
| 4 | Agree |
| 5 | Strongly agree |

Definitions

Metropolitan area

A metropolitan area is a region consisting of a densely populated urban core and its less-populated surrounding territories.

Small city

A city is a relatively large and permanent and has a particular administrative, legal, or historical status based on local law.

Criteria comparison

Here the objective is to evaluate the aforementioned criteria through pairwise comparison to highlight the importance of different criterion compare to each other with the goal of reducing CO₂ emissions in transportation sector. With this goal in mind, please evaluate the following statements:

| Consider a metropolitan area such as Dallas, TX | |
|--|---|
| <i>How you do you agree with these statements?</i> | |
| Air pollution is more important than traffic congestion. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Air pollution is more important than investment cost. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Air pollution is more important than saving natural places. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Traffic congestion is more important than investment cost. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Traffic congestion is more important than saving natural places. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Investment cost is more important than saving natural places. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |

| Consider a small city such as Lubbock, TX | |
|--|---|
| <i>How you do you agree with these statements?</i> | |
| Air pollution is more important than traffic congestion. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Air pollution is more important than investment cost. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Air pollution is more important than saving natural places. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Traffic congestion is more important than investment cost. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Traffic congestion is more important than saving natural places. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Investment cost is more important than saving natural places. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |

Strategy comparison

Here the objective is to evaluate the aforementioned strategies through pairwise comparison. Please evaluate the following statements based the criterion defined for each section:

| Consider <u>the criterion</u> is Reduce air pollution | |
|--|---|
| <i>How you do you agree with these statements?</i> | |
| Reducing strategy better meets the goal in comparison to avoiding strategy. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Reducing strategy better meets the goal in comparison to replacing strategy. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Avoiding strategy better meets the goal in comparison to replacing strategy. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |

| Consider <u>the criterion</u> is Reduce investment cost | |
|--|---|
| <i>How you do you agree with these statements?</i> | |
| Reducing strategy better meets the goal in comparison to avoiding strategy. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Reducing strategy better meets the goal in comparison to replacing strategy. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Avoiding strategy better meets the goal in comparison to replacing strategy. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |

| Consider <u>the criterion</u> is Reduce traffic congestion | |
|--|---|
| <i>How you do you agree with these statements?</i> | |
| Reducing strategy better meets the goal in comparison to avoiding strategy. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Reducing strategy better meets the goal in comparison to replacing strategy. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Avoiding strategy better meets the goal in comparison to replacing strategy. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |

| Consider <u>the criterion</u> is Save more natural places | |
|--|---|
| <i>How you do you agree with these statements?</i> | |
| Reducing strategy better meets the goal in comparison to avoiding strategy. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Reducing strategy better meets the goal in comparison to replacing strategy. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |
| Avoiding strategy better meets the goal in comparison to replacing strategy. | |
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 <input type="checkbox"/> 3 <input type="checkbox"/> 4 <input type="checkbox"/> 5 |
| Strongly disagree | Strongly agree |

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